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Th2C-4

Heart Rate Detection with Hilbert Vibration Decomposition Algorithm in Large-Scale Random Body Movements Based on FMCW Radars

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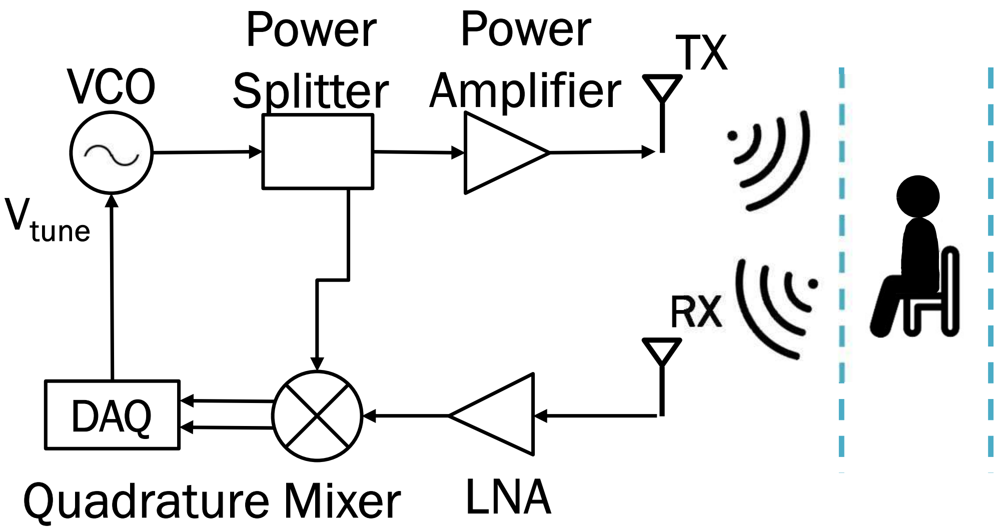
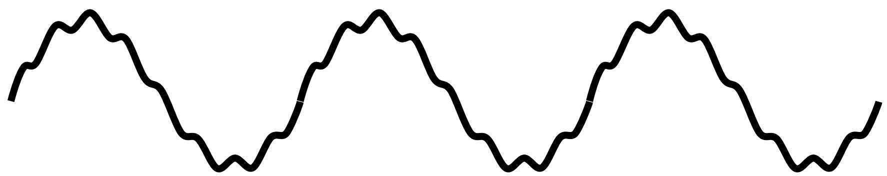
Outline

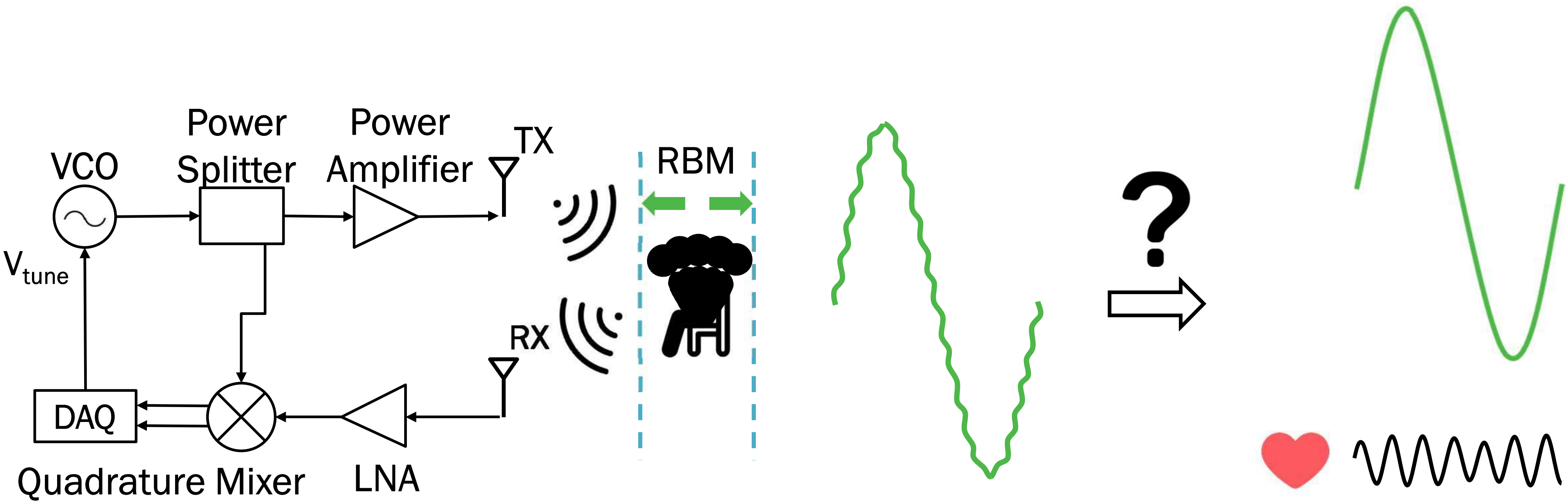
- Introduction and Motivation
- Literature Review
- Theory Analysis
- Proposed Method
- Measurement Results
- Conclusion

Introduction (1/2)





Introduction (2/2)



Motivation (1/2)

- Motivation
  - The environments are non-stationary in most of application scenarios
  - Non-stationary clutter is aperiodic and uncertain
  - The presence of RBM can seriously interfere with the extraction of vital signs
  - Heart rate is difficult to identify compared with respiration
- Goal
  - Heart rate detection in large-scale RBM based on FMCW radars

RBM: random body movement, FMCW: frequency modulated continuous wave

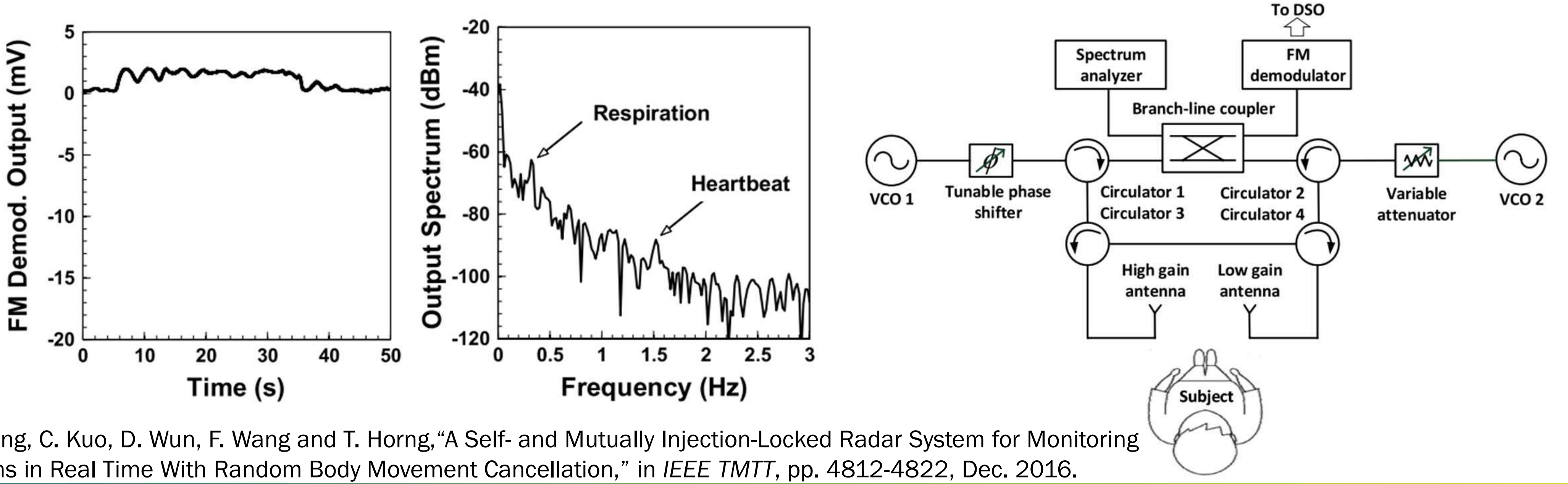
Motivation (2/2)

- Problem solution
  - FMCW radar system → Suitable SNR, Range resolution
  - Hilbert Vibration Decomposition (HVD) → Cancellation RBM
  - Masking signal HVD (M-HVD)→ Enhancing SNR
- Challenge
  - Accuracy of heartbeat extraction
  - Reduce non-vital signs interference
  - The SNR of heartbeat (quantify the effect of noise on heartbeat estimation)

SNR: signal-to-noise ratio

Literature Review (1/3)

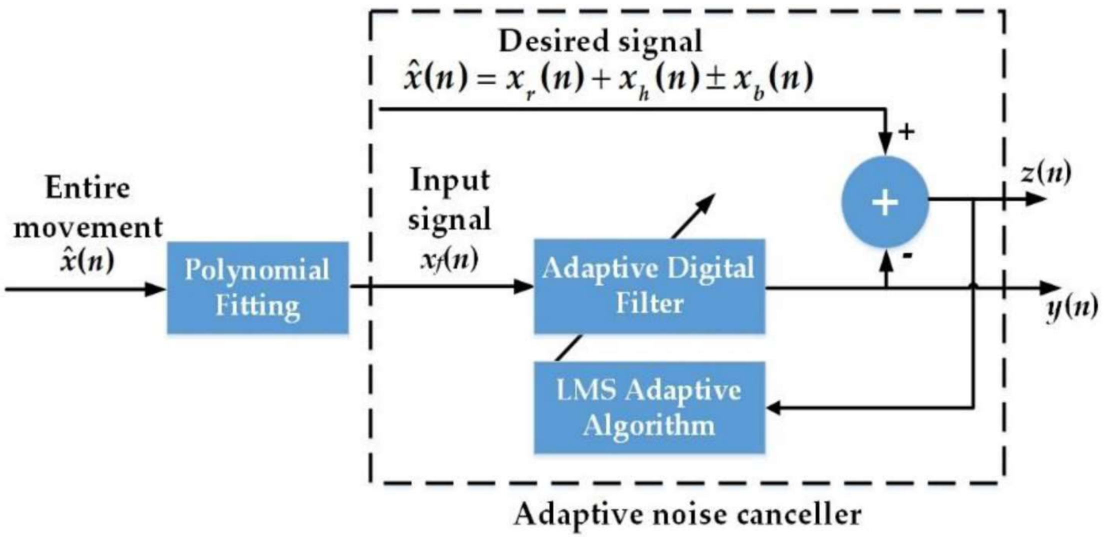
- Self- and Mutually Injection-Locked (SMIL) [1]
  - ✓The resultant Doppler FMs of the two VCOs are out of phase and equal in magnitude, canceling each other out in the MIL process
  - X The complexity of the system makes the actual measurement difficult

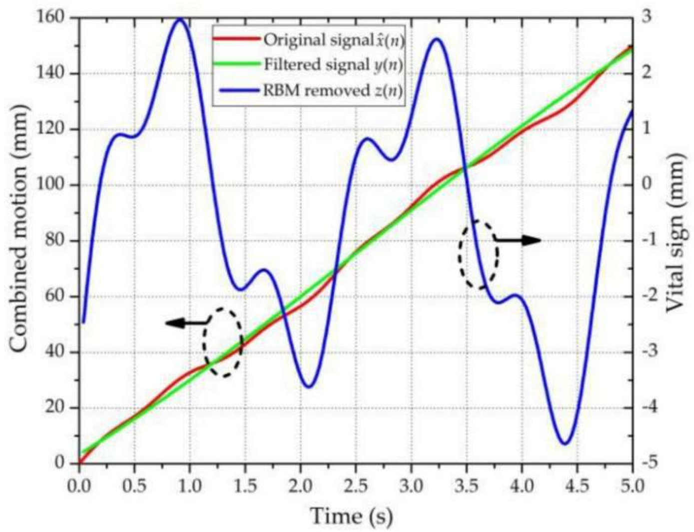


[1] M. Tang, C. Kuo, D. Wun, F. Wang and T. Horng,"A Self- and Mutually Injection-Locked Radar System for Monitoring Vital Signs in Real Time With Random Body Movement Cancellation," in *IEEE TMTT*, pp. 4812-4822, Dec. 2016.

Literature Review (2/3)

- Adaptive Noise Cancellation (ANC) [2]
  - ✓Polynomial fitting method to extract vital signs in the large-scale RBM
  - ✗ Not choosing the correct step-size affects convergence speed

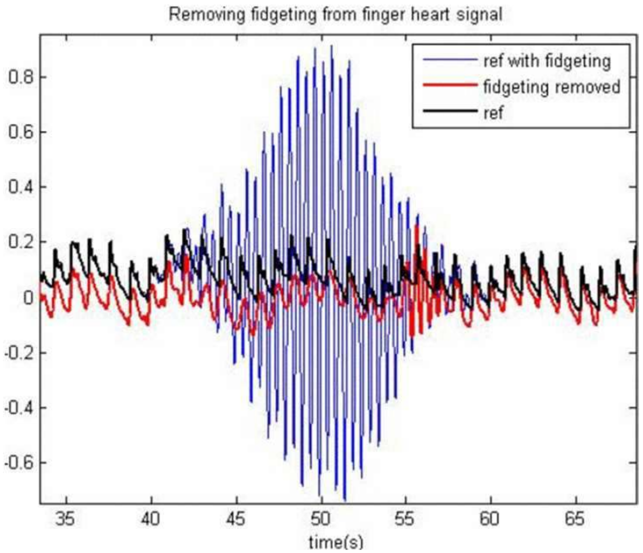


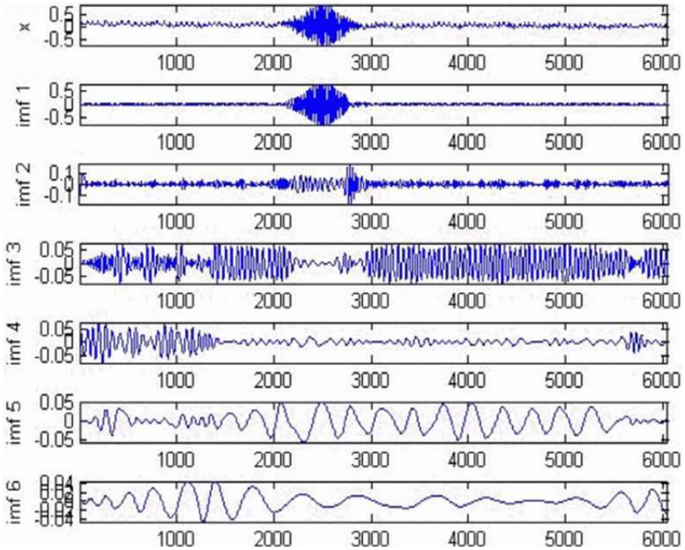


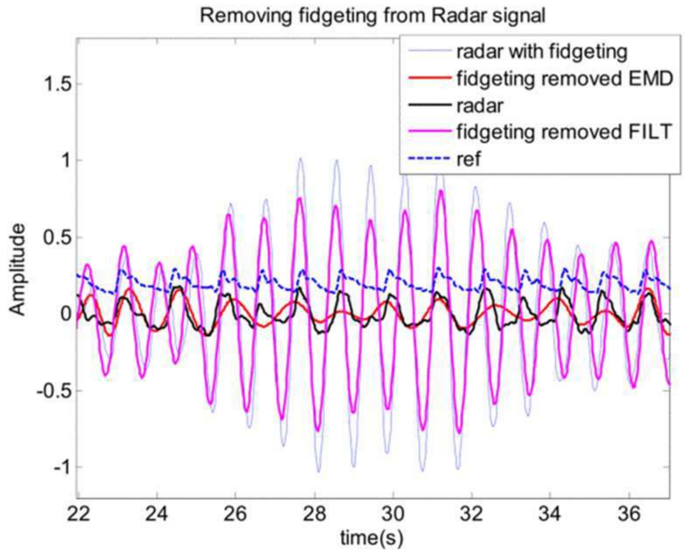
[2] Z. Yang, H. Shi, S. Zhao, X. Huang,"Vital Sign Detection during Large-Scale and Fast Body Movements Based on an Adaptive Noise Cancellation Algorithm Using a Single Doppler Radar Sensor, " in *Sensors*, vol. 20, no. 15, pp.4183, 2020.

Literature Review (3/3)

- Empirical Mode Decomposition (EMD) [3][4]
  - ✓EMD was applied to removing fidgeting motion
  - ✗ The signals are close in frequency, mode mixing problem occurs easily







[3] I. Mostafanezhad, O. Boric-Lubecke, V. Lubecke and D. P. Mandic, “Application of empirical mode decomposition in removing fidgeting interference in doppler radar life signs monitoring devices, ” in 2009 Annu Int Conf IEEE Eng Med Biol Soc ., pp. 340-343, 2009.
[4] C. -Y. Huang, G. -W. Fang, H. -R. Chuang and C. -L. Yang, "Clutter-Resistant Vital Sign Detection Using Amplitude-Based Demodulation by EEMD-PCA-Correlation Algorithm for FMCW Radar Systems," 2019 EuMC, Paris, France, pp. 928-931, 2019.

Theory Analysis (1/6)

- The reflected signal from target is received by the FMCW

$$S_B(t) = A_d\, exp\left(j\left(2\pi f_b t + \frac{4\pi f_c R(\tau)}{c} + \Delta\phi_0(t)\right)\right) \qquad (1)$$
$$+A_c\, exp\left(j\left(2\pi f_{bc} t + \frac{4\pi f_c R_c(\tau)}{c} + \Delta\phi_c(t)\right)\right)$$

where

A_d, A_c: the amplitudes of the beat signal from target and non-stationary clutter

f_b, f_{bc}: the beat frequency of the target and non-stationary clutters

$R(\tau)$, $R_c(\tau)$: the distances of the radar system relative to the target and the non-stationary clutter

ϕ_0, ϕ_c: residual phase noise

Theory Analysis (2/6)

- To extract the phase information, the signal from the target range bin

$$S_B(\tau) = A_d \exp(j\varphi_t) + A_c \exp(j\varphi_c) \qquad (2)$$

Vital signs

$$\varphi_t = j\frac{4\pi f_c \cdot R(\tau)}{c}$$

Non-stationary Clutter

$$\varphi_c = j\frac{4\pi f_c \cdot R_c(\tau)}{c}$$

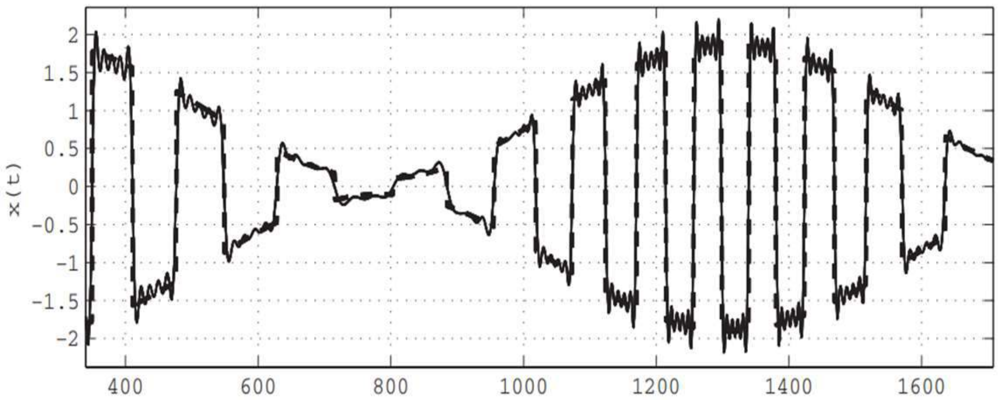
where

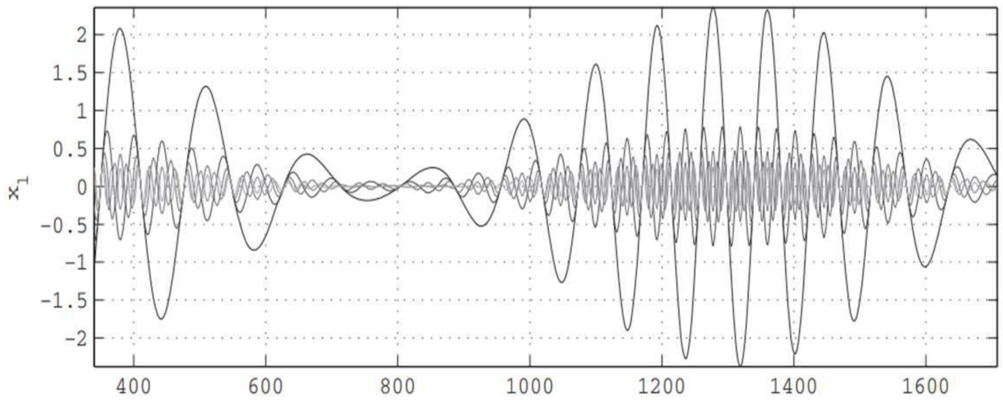
A_d, A_c: the amplitudes of the beat signal from target and non-stationary clutter

$R_c(\tau)$: distance and vibration of non-stationary clutter

Theory Analysis (3/6)

- Characteristics of HVD
  - To HVD method, dedicated to the problem of decomposition of nonstationary vibration [5]
  - The first component separated from the initial vibration contains the varying highest amplitude. The residual signal contains information of other lower amplitude components





[5] Feldman, Michael. Hilbert transform applications in mechanical vibration. John Wiley & Sons, 2011.

Theory Analysis (4/6)

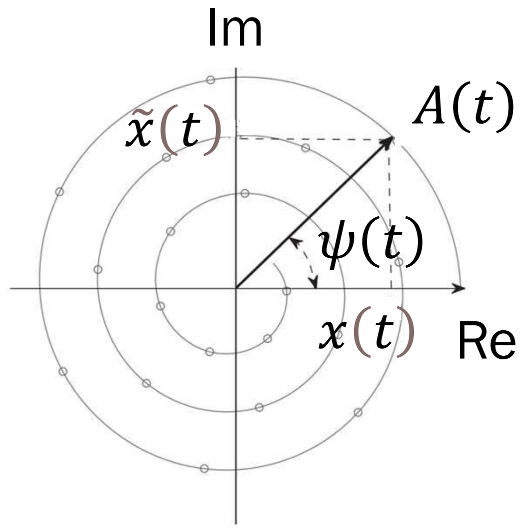
- HVD is based on Hilbert Transform (HT) and analytical signal

analytic signal $X(t) = x(t) + i\tilde{x}(t) = A(t)e^{j\psi(t)}$ (3) $\tilde{x}$: the HT of $x(t)$

instantaneous amplitude $A(t) = \sqrt{x(t)^2 + \tilde{x}(t)^2}$ (4)

instantaneous phase $\psi(t) = \arctan \frac{\tilde{x}(t)}{x(t)}$ (5)

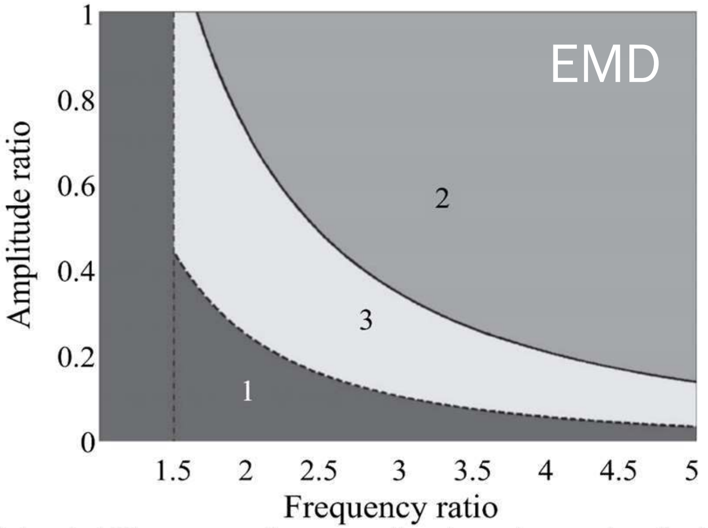
instantaneous frequency $\omega(t) = \dot{\psi}(t)$ (6)

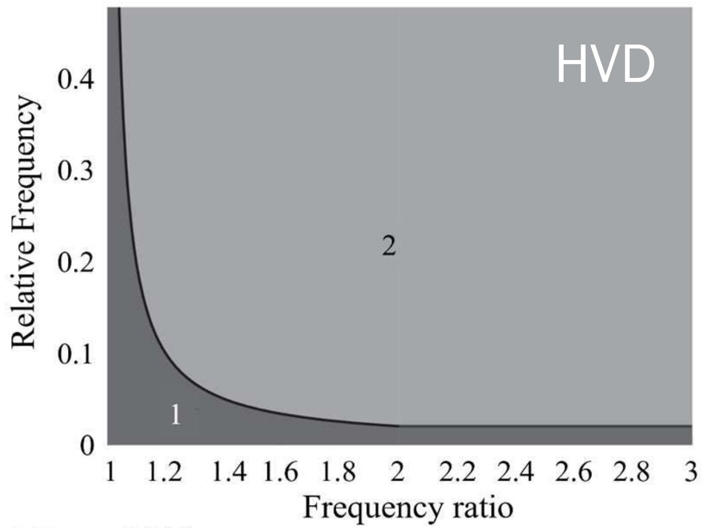


[5] Feldman, Michael. Hilbert transform applications in mechanical vibration. John Wiley & Sons, 2011.

Theory Analysis (5/6)

- HVD frequency resolution
  - HVD decomposes the initial signal to slow varying part and faster varying part
  - HVD with better frequency resolution capacity, decompose frequencies closer than EMD [5]





[5] Feldman, Michael. Hilbert transform applications in mechanical vibration. John Wiley & Sons, 2011.

Theory Analysis (6/6)

- Synchronous demodulation
  - To extract the amplitude of a known frequency by multiplying the initial component by a reference signal $r(t) = \cos\left(\int \omega_r(t)dt\right)$

$$x(t) = \sum A_l(t)\cos\left(\int \omega_l(t)dt + \varphi_l\right) \quad (7) \qquad \tilde{x}(t) = \sum A_l(t)\sin\left(\int \omega_l(t)dt + \varphi_l\right) \quad (8)$$

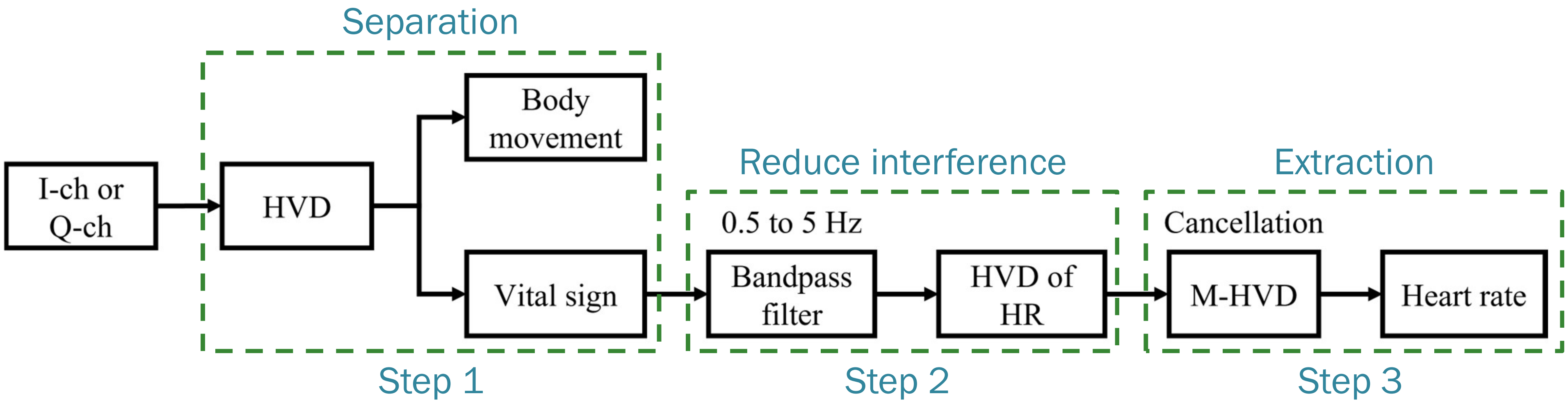
$$x_l(t) = x(t) \times r(t) = \frac{1}{2}A_l(t)[\cos(\varphi_l(t)) + \cos(\int (\omega_l(t) + \omega_r(t))dt + \varphi_l(t))] \quad (9)$$

$$\tilde{x}_l(t) = \frac{1}{2}A_l(t)[-\sin\left(\varphi_l(t)\right) - \sin(\int (\omega_l(t) + \omega_r(t))dt + \varphi_l(t))] \quad (10)$$

$$A_l(t) = \sqrt{x_l(t)^2 + \tilde{x}_l(t)^2} \quad (11) \qquad \varphi_l(t) = \arctan\frac{x_l(t)}{\tilde{x}_l(t)} \quad (12)$$

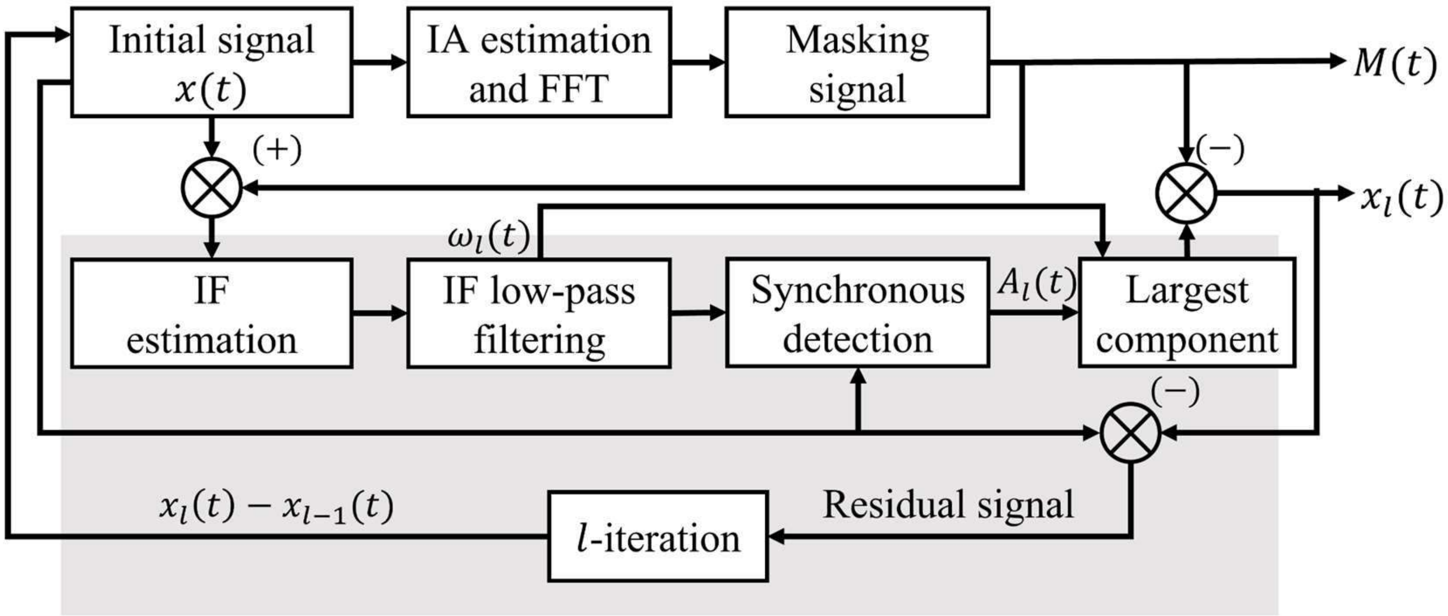
Proposed Method (1/3)

- The proposed algorithm consists of three steps:
  1. Separates the RBM from the vital signs
  2. Reduce interference from the non-stationary clutter and extract the heartbeat
  3. Reduce the error rate, interference signal and improve SNR



Proposed Method (2/3)

- Block diagram of masking signal HVD. The gray area is HVD
  - HVD: separation of nonstationary vibration into simple components
  - M-HVD: improve the signal separation performance



IA: instantaneous amplitude; IF: instantaneous frequency

Proposed Method (3/3)

- Masking signal HVD (M-HVD)
  - The maximum amplitude FFT of the initial signal is proposed as masking signal to improve the non-stationary synthetic signals [6]
  - The initial signal is added and the new signal $x_m(t) = x(t) + M(t)$

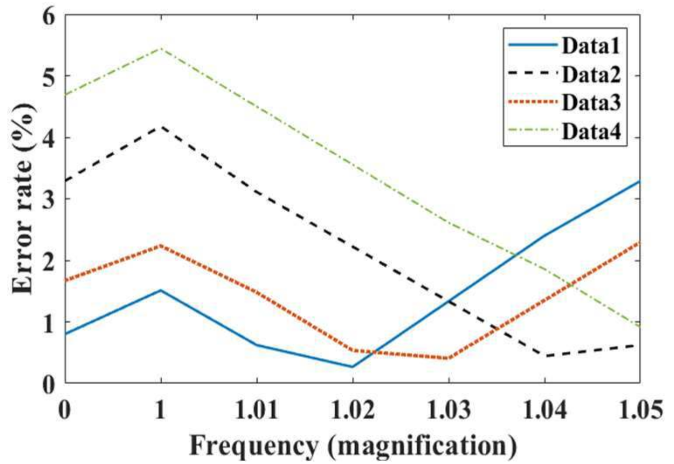
$M(t) = A_m \sin(2\pi f_m t)$

A_m is obtained as the average amplitude of $1.6 \times A(t)$

$A(t) = \sqrt{x(t)^2 + \tilde{x}(t)^2}$

The largest FFT spectrum amplitude is define as f

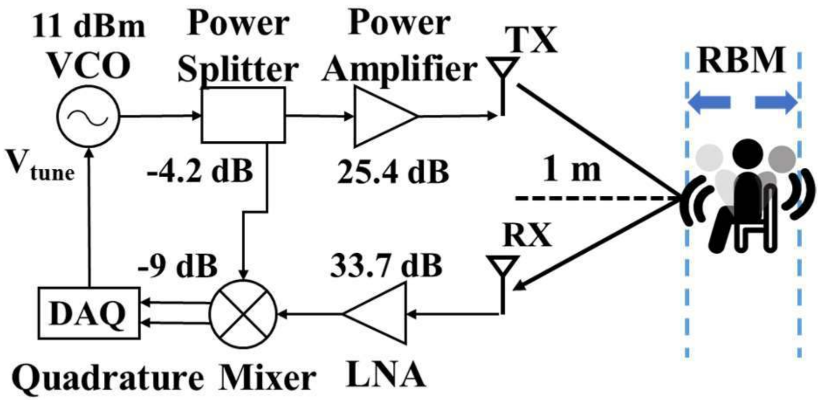
$f_m = 1.02 \times f$

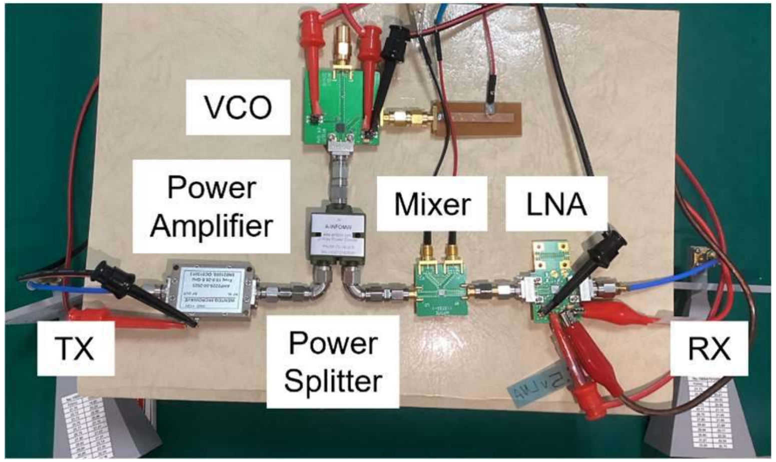


[6] J. J. Ramos, J. I. Reyes and E. Barocio, "An improved Hilbert Vibration Decomposition method for analysis of low frequency oscillations," 2014 IEEE PES Transmission & Distribution Conference and Exposition - Latin America (PES T&D-LA), 2014, pp. 1-6.

Experiment Setup

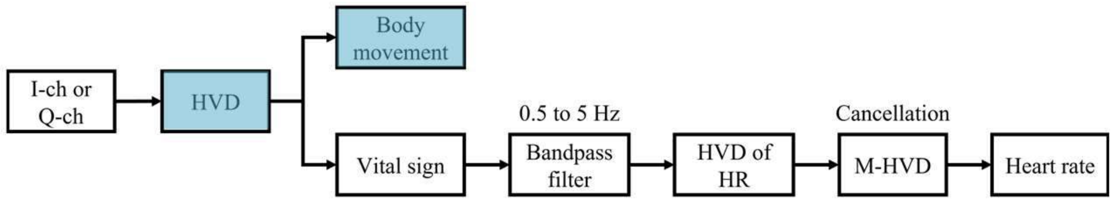
Parameter	Value
Central Modulation Frequency	24 GHz
Modulation Bandwidth	250 MHz
Pulse Repetition Interval	2 ms
Range Resolution	0.6 m
Measurement Period	60 sec
RBM velocity	1.6 $^{cm}/_{s}$

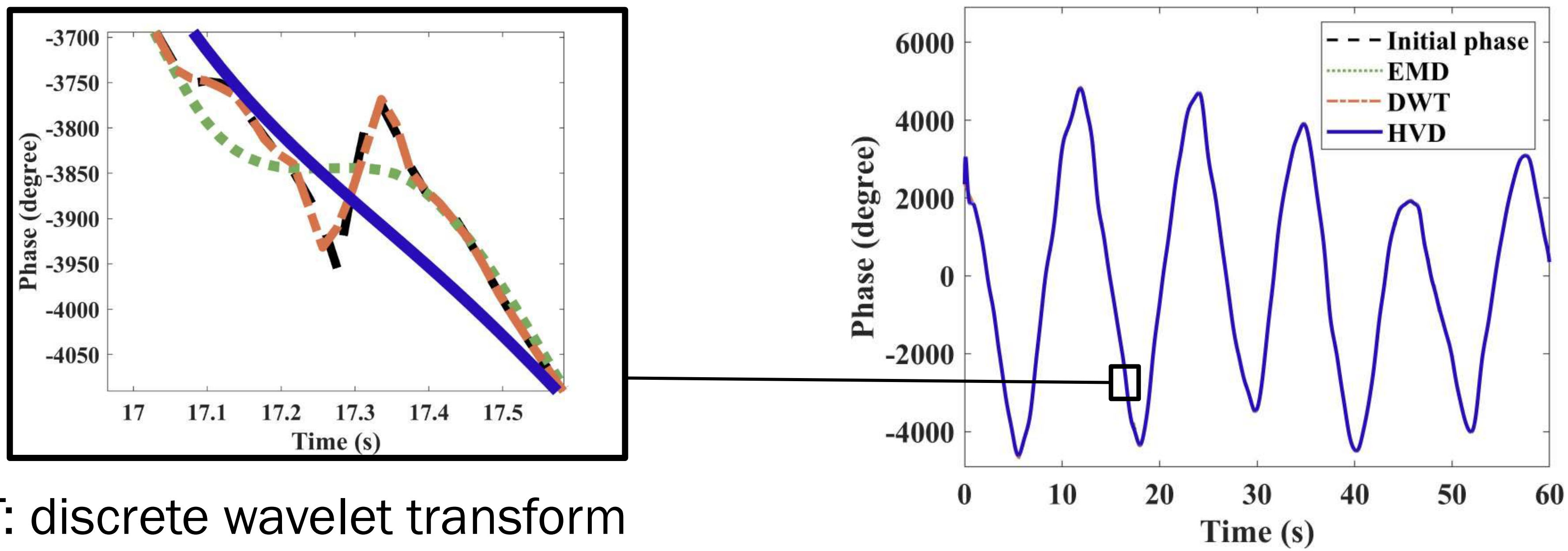




Measurement Results – Step 1

Comparison of the target phase with the decomposition following HVD, EMD and DWT



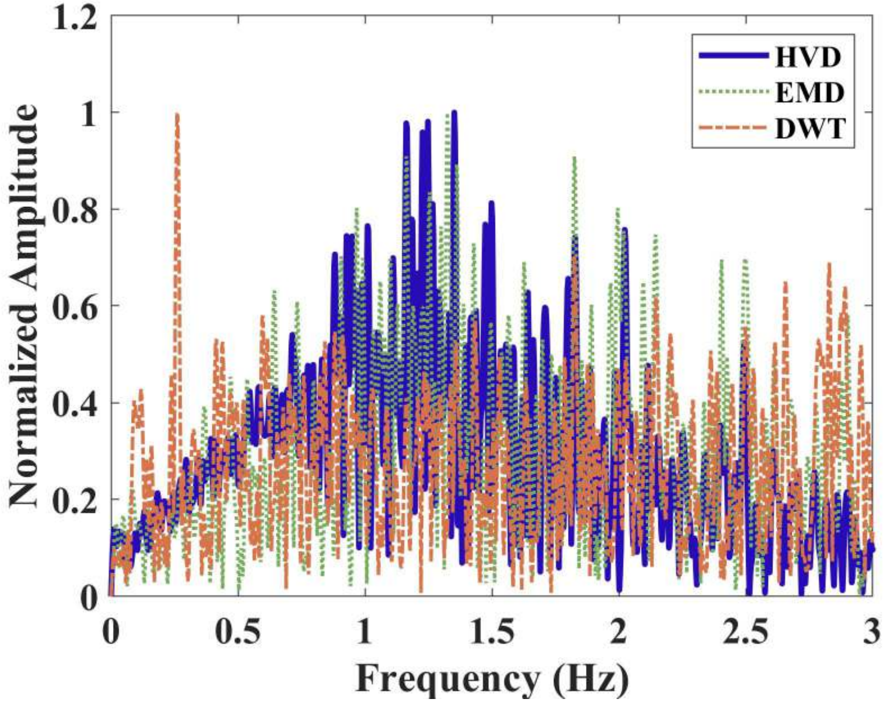


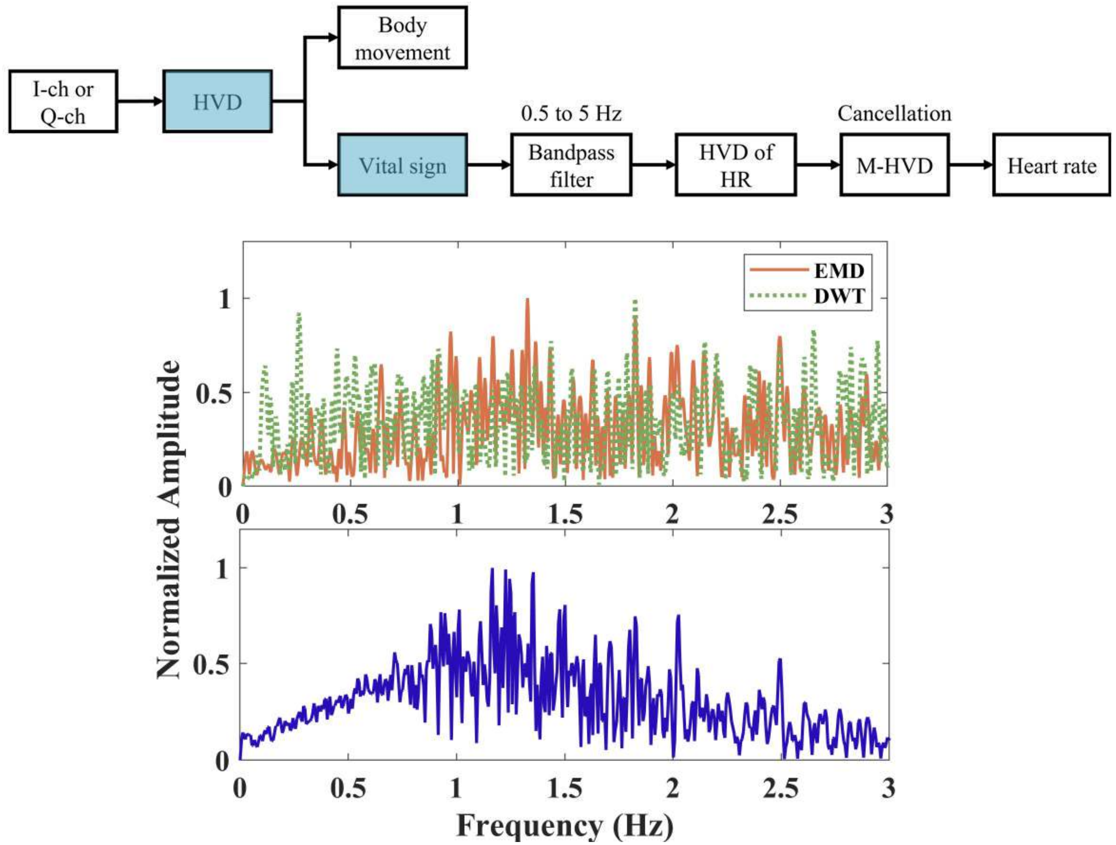
DWT: discrete wavelet transform

Measurement Results – Step 1

Comparison among EMD, DWT, and HVD

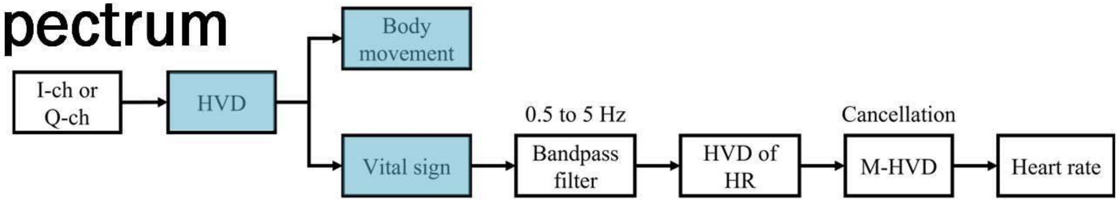
Phase spectrum of RBM after cancellation of HVD, EMD, DWT

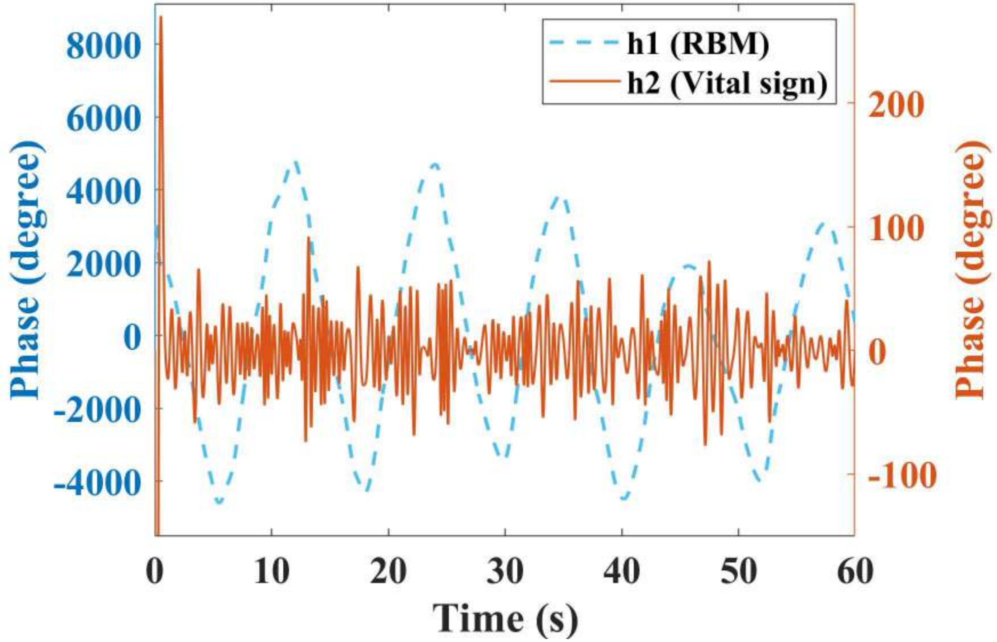


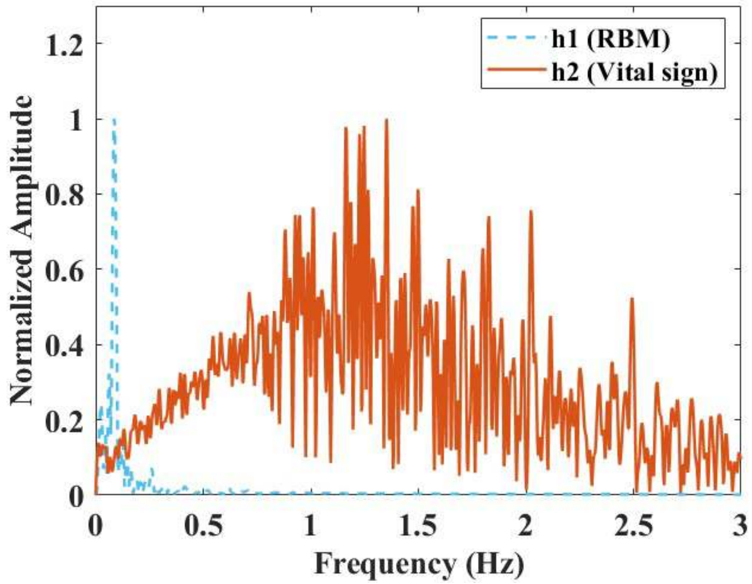


Measurement Results – Step 1

Separation of RBM signal from vital signs by first-stage HVD of the component phase and frequency spectrum

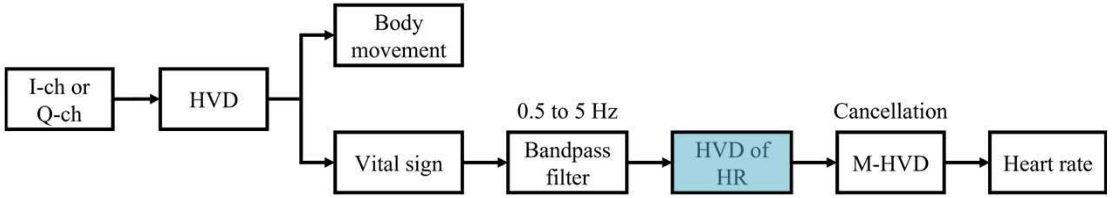


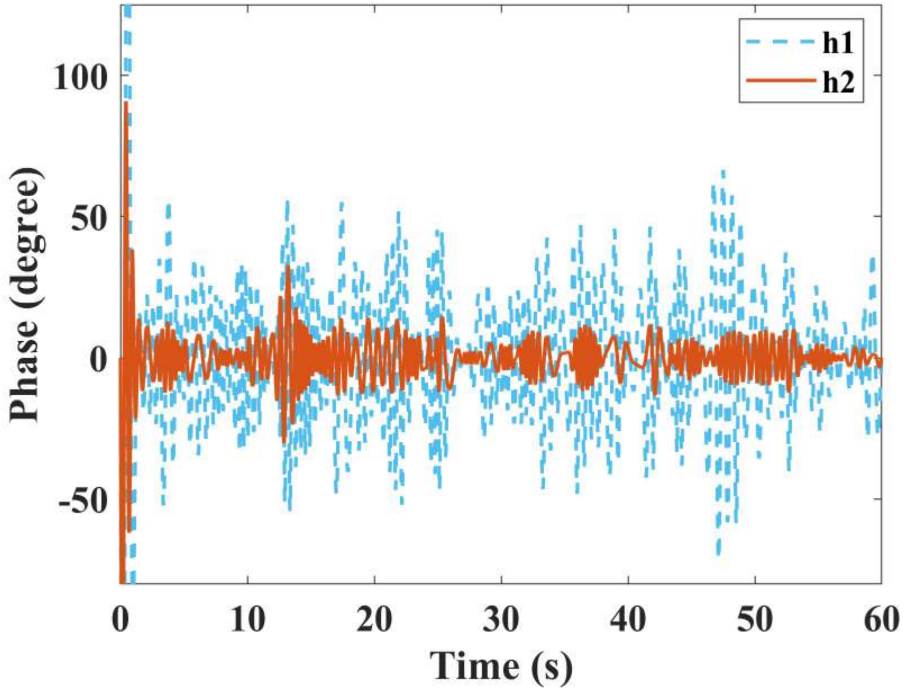


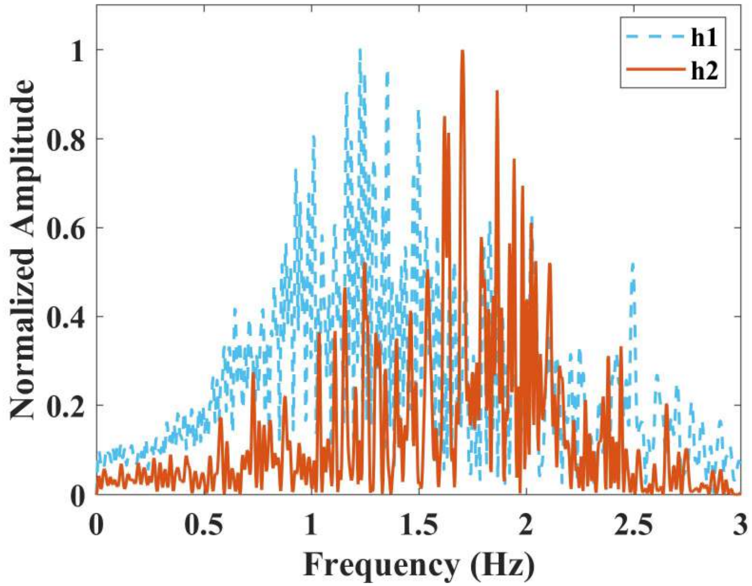


Measurement Results – Step 2

The phase and spectrum of the component after the first stage HVD is separated by second stage HVD

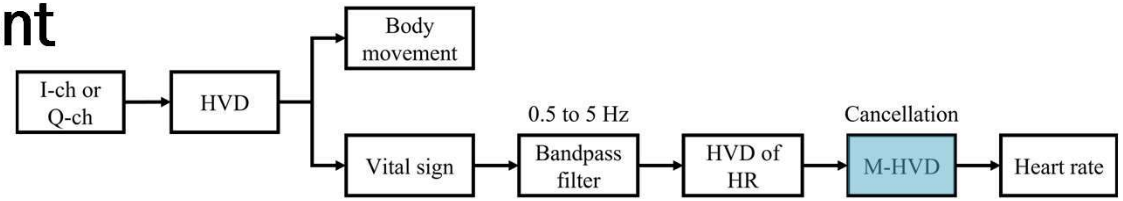


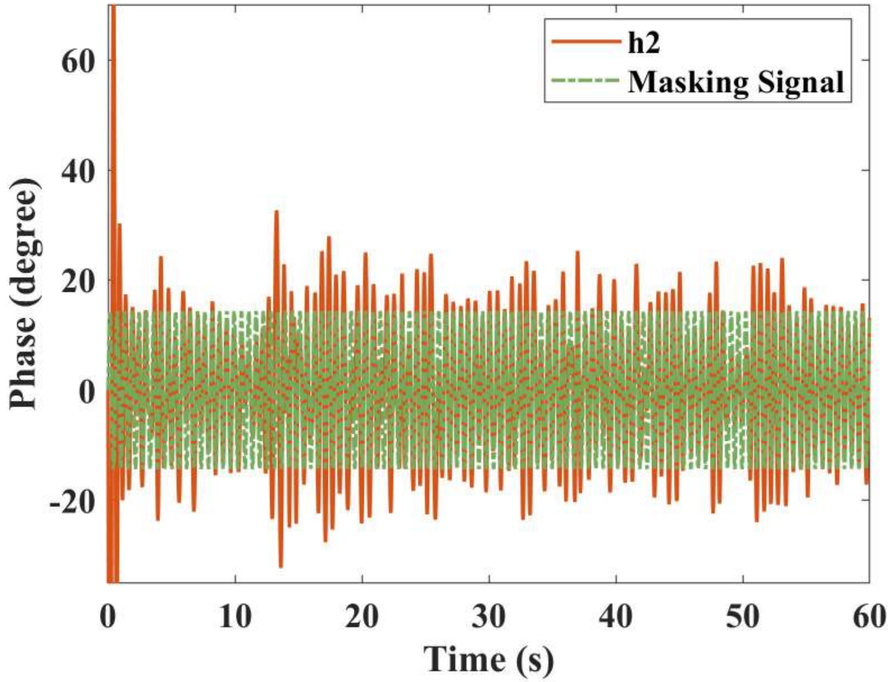


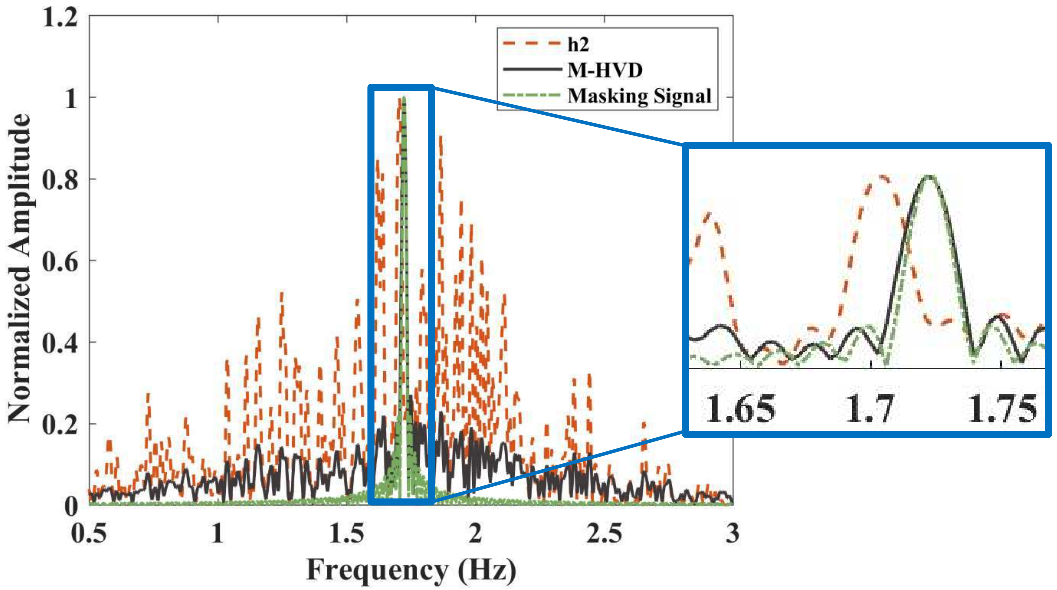


Measurement Results – Step 3

Comparison of the spectrum before and after adding the masking signal to the second stage HVD component

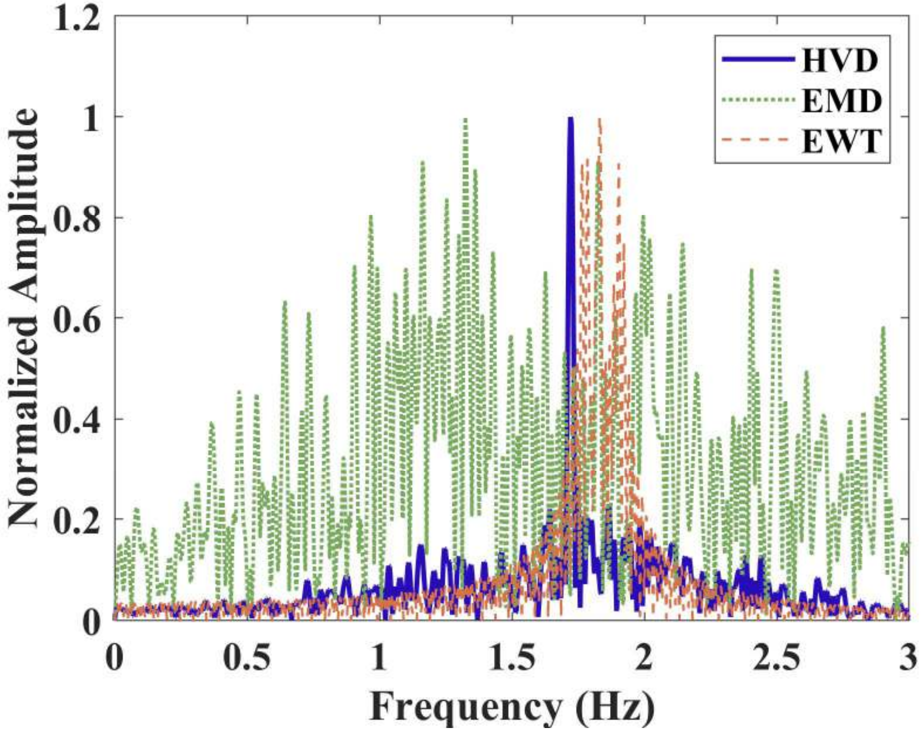






Measurement Results – Step 3

Results of frequency spectrum processed by the proposed HVD compared to EMD and EWT



EWT: empirical wavelet transform

Measurement Results

- In addition to the comparison of spectrum results, the relative error, SNR and computational load are also used for comparison

SNR $$SNR_{0\sim3Hz,dB} = 10\log\frac{P_{signal}}{P_{noise}}$$

Average relative error $$Error_{HR}(\%) = \frac{1}{N}\sum_{k=1}^{N}\frac{\left|HR_{HVD,k} - HR_{Ref,k}\right|}{HR_{Ref,k}} \times 100\,\%$$

Algorithm	HR Error (%)	SNR (dB)	Processing Time (s)
EMD	46.22	7.02	0.083
EWT	2.75	19.36	0.066
HVD	2.61	23.04	0.633
This work	1.64	27.73	0.883

Measurement Results

- Literature Comparison

	System	Method	Range	HR Error
Liu et al. [7]	77 GHz FMCW	DRSEPK	1 m	4.68 %
Yin et al. [8]	8.5 GHz IR-UWB	HEAR	1 ~ 2 m	6.15 %
This work	24 GHz FMCW	HVD	1 m	1.64 %

[7] L. Liu, S. Zhang and W. Xiao, "Non-Contact Vital Signs Detection Using mm-Wave Radar During Random Body Movements," 2021 IEEE 16th Conference on Industrial Electronics and Applications (ICIEA), 2021, pp. 1244-1249.
[8] Yin, W.; Yang, X.; Li, L.; Zhang, L.; Kitsuwan, N.; Oki, E. HEAR: Approach for Heartbeat Monitoring with Body Movement Compensation by IR-UWB Radar. Sensors 2018, 18, 3077

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Conclusion

- Proposed an HVD algorithm for non-contact vital sign detection using FMCW radar in large-scale RBM
- HVD effectively separates the large-scale RBM from the vital signs
- Result of signal processing have the average relative error 1.64%, and SNR improvement of 8.3 dB compared with EWT
- Advantage of the proposed algorithm:
  – High accuracy
  – High SNR
  – Low computational load

Thanks for your attention.

Questions?

Feel free to contact us!

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